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Low-Cycle Fatigue of Nonferrous Alloys for Heat Exchangers and Saltwater Piping

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ABSTRACT

This is the fourth phase report of an investigation of the low-cycle fatigue behavior of nonferrous alloys for submarine heat exchanger and saltwater piping applications. The low-cycle fatigue behavior of forged Ni-Al bronze and cast valve bronze was investigated in both air and salt water. The flexural fatigue behavior of these two materials, together with cast Ni-Al bronze and cast Monel* "E" of phase three, were compared to that predicted by Langer's equation. It was concluded that Langer's equation was [illegible] overly conservative for the materials reported, and that saltwater corrosion has very little effect on low-cycle fatigue life. Both cast and forged Ni-Al bronze rank as superior, whereas valve bronze ranks poorly as far as low-cycle fatigue performance is concerned.

*Registered trade name of the International Nickel Company, Incorporated

ADMINISTRATIVE INFORMATION

The low-cycle fatigue of nonferrous alloys for heat exchangers and saltwater piping was authorized under Sub-project S-F020 01 02, Task 0725

REFERENCES

(a) NAVENGRXSTA Rept 910196A of 20 Jun 1962
(b) MEL Rept 86 103A of 10 Sep 1963
(c) MEL Rept 199/64 of 8 Sep 1964
(d) NAVENGRXSTA Rept 91 197D of 14 Feb 1963
(e) Langer, B. F., "Design of Pressure Vessels for Low-Cycle Fatigue," ASME Trans, Vol. 84, Series D, No. 3, Sep 1962, pp. 389-399

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LOW-CYCLE FATIGUE OF NONFERROUS ALLOYS FOR HEAT EXCHANGERS AND SALTWATER PIPING

1.0 INTRODUCTION

1.1 Background. This investigation was conducted to further study the low-cycle fatigue behavior of nonferrous alloys for heat exchangers and saltwater piping, particularly for use in submarine applications where exposure to full sea pressure during submergence is involved. This report is the fourth in a series. References (a), (b), and (c), the first three reports, covered the following:

- Reference (a) - Low-cycle fatigue behavior in air and salt water of cast gun metal, cast Superston 40, wrought Monel, and wrought 70-30 cupronickel.

- Reference (b) - Low-cycle fatigue behavior of cast 70-30 cupronickel, wrought 90-10 cupronickel, wrought Cufenloy 40, and wrought cupronickel 707.

- Reference (c) - Low-cycle fatigue behavior of cast Ni-Al bronze and cast Monel "E"; low-cycle corrosion--fatigure results for cast 70-30 cupronickel, wrought 90-10 cupronickel, and wrought Cufenloy 40; and high-cycle fatigue behavior of all alloys investigated in previous reports.

From the foregoing investigations, the following conclusions were made:

- Saltwater corrosion is not an important factor in the low-cycle fatigue behavior of the nonferrous alloys investigated.

- The low-cycle fatigue behavior of wrought Monel, wrought Superston 40, and Cufenloy 40 (drawn and stress relieved) is superior to that of the other materials when compared on the basis of either nominal or pseudoelastic stress.

- The low-cycle fatigue behavior of cast materials is erratic; that of wrought materials is more consistent, and thus, more predictable.

- Langer's equation gives a good estimate of the fatigue relationships for wrought materials, but is overly conservative in the low-cycle region for cast materials.

1.2 Present Investigation. The fatigue properties of forged Ni-Al bronze and cast valve bronze were obtained over a life range of 100 to 100-million cycles. In addition, six low-cycle corrosion-fatigue tests were performed on these and two other alloys, namely cast Ni-Al bronze and cast Monel "E." The fatigue results of the four alloys were compared with those predicted by Langer's emperical equation. Also, nine low-cycle fatigue tests were made on weldments of 70-30 Cu-Ni welded to 70-30 Cu-Ni, Monel welded to Monel, and Monel welded to steel.

2.0 DESCRIPTION OF MATERIAL

The source, condition, composition, and mechanical properties of the new materials in the program, forged Ni-Al bronze and valve bronze, are listed in Table 1. The true-stress/true-strain curves for these materials are shown in Figure 1, along with a mathematic expression of the true-stress/true-strain relationship in the form of the equation

$$\bar{\sigma} = K\bar{\epsilon}^{n} \quad ;$$

where

$\bar{\sigma}$ = true stress, psi*
K = strength coefficient, psi
$\bar{\epsilon}$ = true strain, in/in.
n = strain hardening coefficient.

Fracture stresses have been corrected by Bridgman's correction factor. Because of the differences observed in the tensile properties of the two Ni-Al bronze plates, two curves are shown in

*Abbreviations used in this text are from the GPO Style Manual, 1959, unless otherwise noted.

Figure 1 for this material. Information for the cast Ni-Al bronze and cast Monel "E" was presented previously in reference (c).

Table 1

Additional Materials Investigated

Alloy	Source of Material	Condition As Received	MEL Designation	Chemical Composition % (Manufacturer's Analysis)								
				Cu	Ni	Fe	Al	Mn	Zn	Sn	Pb	P
Ni-Al Bronze (Forged)	Philadelphia Bronze & Brass Corp	Plate, Forged QQB-679 Comp 2, Annealed	DZE	81.18	4.50	2.75	10.56	0.89	--	NIL	--	--
Valve Bronze (Cast)	Philadelphia Bronze & Brass Corp	Plate, As Cast MIL-B-16541	DZU	88.47	0.53	0.01	--	--	3.76	5.59	1.63	0.01

Mechanical Properties

Alloy	Testing Laboratory	0.2% Yield Strength PSI	Tensile Strength PSI	Elongation in 2 in. %	Reduction in Area %	Rockwell Hardness "B"	Modulus of Elasticity PSI
Forged Ni-Al Bronze	Philadelphia Bronze & Brass Corp	47,200	97,600	14	--	--	17 x 10^6
Plate 1	MEL[1]	59,900	117,300	10	12	99	
Plate 100	MEL[1]	43,900	89,400	24	22	--	
Cast Valve Bronze	Philadelphia Bronze & Brass Corp	--	39,800	34	--	--	14 x 10^6
Plate 1	MEL[1]	15,500	27,900(2)	18(2)	20	39	
Plate 50	MEL[1]	16,200	28,000(2)	15(2)	19	--	

[1] MEL results are the average of two tests.
[2] Below specification MIL-B-16541 requirements for separately cast tensil coupons (34,000 psi tensil strength; 22% elongation).

3.0 METHOD OF TEST

3.1 Low-Cycle Fatigue Tests. The low-cycle flexural fatigue tests were conducted in the manner described in reference (d). Each test consisted of subjecting a beam specimen, similar to that shown in Figure 2, to cycles of completely reversed alternating bending strain. Except where otherwise noted, the tests were conducted in air at a cyclic rate of 5 cpm, and were controlled by electrical timers with beam deflection limited by mechanical stops. By controlling the movement of the load arm, the dwell time at the maximum deflection limits was made approximately 90 percent of the cycle period. The resultant strain versus time pattern was essentially a square wave.

3.2 Corrosion--Fatigue Tests. Low-cycle flexural fatigue tests of the type described previously were carried out in an environment of salt water. A deflection level which previously had produced approximately a 20,000 cycle life in air was used, with cyclic rates of 0.25 and 0.10 cpm. Severn River water was continuously dripped on the test section of the specimens. This water is a brackish estuary water containing 1/6 to 1/3 of the salt content of seawater, depending on the season and tide.

3.3 Low-Cycle Fatigue Tests of Weldments. The procedure used in testing the weldments was identical to that described in paragraph 3.1, except that the test section of the specimen was modified as shown in Figure 3. This modification produced essentially constant stress conditions in the base metal, weld metal, and heat affected zone.

3.4 High-Cycle Fatigue Tests. High-cycle fatigue data were obtained from a constant-load rotating-cantilever beam test. The specimen (Figure 4) was run in a double-end, dead-weight load machine operating at 1450 cpm in air.

4.0 RESULTS

4.1 Low-Cycle Fatigue Tests. For each low-cycle fatigue specimen, a hysteresis loop similar to the one shown in Figure 5 was recorded. From this loop, the total moment range (ΔM), plastic strain range ($\Delta \epsilon_p$), and total strain range ($\Delta \epsilon_T$) were measured. The nominal reversed stress, S_R, was calculated by the equation:

$$S_R = \frac{M_R \cdot c}{I} \;;$$

where

M_R = maximum reversed moment (Figure 5), in-lb
c = distance from neutral axis to outermost fiber at minimum cross section, in.
I = moment of inertia at minimum cross section, $in.^4$

The reversed pseudoelastic stress, S_{PE}, was calculated by the equation:

$$S_{PE} = \frac{E}{2} (\Delta\epsilon_T) \quad ;$$

where

E = modulus of elasticity, psi
$\Delta\epsilon_T$ = total strain range (Figure 5), in/in.

The data for the low-cycle fatigue tests, except for the weldment tests, are summarized in Table 2.

Table 2

Low-Cycle Flexural Fatigue Data

Material	Test Environment	Total Moment Range ΔM In-Lb	Plastic Strain Range $\Delta\epsilon_p$ In/In	Total Strain Range $\Delta\epsilon_T$ In/In	Nominal Reversed Stress S_R PSI	Pseudo-Elastic Stress S_{PE} PSI	No. of Cycles to Failure N	Cycle Rate CPM	Specimen Number
Ni-Al Bronze Cast	Air	11,400	0.00187	0.00807	54,700	72,500	38,348	5	DYO-799
	Salt Water	13,100	0.00172	0.00986	62,900	89,000	12,288	0.1	DYO-1
Monel "E" Cast	Salt Water	8,750	0.00075	0.00450	42,000	52,000	31,303+	0.1	DZA-50
Ni-Al Bronze Forged	Air	19,600	0.00906	0.02130	94,100	182,000	1,430	5	DZE-140
	Air	19,700	0.00537	0.01660	94,600	141,000	2,430	5	DZE-100
	Air	20,200	0.00192	0.01430	97,000	121,000	6,940	5	DZE-40
	Air	18,700	0.00152	0.01300	89,800	110,000	11,030	5	DZE-5
	Air	18,500	0.00086	0.01180	88,700	100,000	18,723	5	DZE-1
	Air	17,650	0.00174	0.01130	84,700	96,000	21,898	5	DZE-145
	Salt Water	19,600	0.00096	0.01240	94,100	106,000	8,492*	0.1	DZE-45
	Salt Water	16,950	0.00380	0.01370	81,400	116,000	4,003	0.25	DZE-105
Valve Bronze Cast	Air	7,000	0.00560	0.01140	33,600	80,000	447	5	DZU-1
	Air	6,600	0.00200	0.00445	31,700	31,000	1,240	5	DZU-5
	Air	6,000	0.00174	0.00558	28,800	39,000	1,511	5	DZU-45
	Air	4,600	0.00082	0.00426	22,100	30,000	4,975	5	DZU-55
	Air	4,900	0.00040	0.00340	23,500	24,000	53,611	5	DZU-90
	Air	2,800	0.00015	0.00273	13,400	19,000	90,664	5	DZU-95
	Salt Water	4,850	0.00112	0.00477	23,300	33,500	373	0.25	DZU-50
	Salt Water	4,500	0.00055	0.00370	21,600	26,000	31,466	0.1	DZU-40

*Complete fracture initiating on underside of specimen.

The low-cycle fatigue characteristics of the forged Ni-Al bronze and cast valve bronze are shown in Figure 6, using the S_R versus N (Cycles to failure) relationship, and in Figure 7, using the S_{PE} versus N relationship. The solid line in each of these plots is the calculated line of best fit for the test data, assuming a log-log linear relationship for the life range studied. The dashed lines are the 95 percent confidence limits.

As was expected, plastic strain measurements on welded specimens showed nonuniform strains along the test length. This was caused by differences in strength properties among the materials comprising the weldment. Accordingly, no attempt was made to correlate strain measurements with fatigue life. Table 3 summarizes the low-cycle fatigue data obtained for the weldments.

Table 3

Results of Low-Cycle Fatigue Tests of Weldments

Material	Nominal Reversed Stress, S_R PSI	No. of Cycles to Failure N	Specimen No.	Remarks
70-30 Cu-Ni Welded to 70-30 Cu-Ni (INCO 137 and 187 Electrode)	48,000	4,440	DUL-290	1
	43,000	13,089	DUL-55	1
	42,000	20,614	DUL-60	1
Monel 400 Welded to Monel 400 (INCO 130 Electrode)	65,000	6,826	DZF-160	2
	65,000	7,680	DZF-150	1 and 2
	58,800	14,886	DZF-155	1
Monel 400 Welded to Steel (Y.P.-47KSI) (INCO 140 Electrode)	67,000	4,777	DZF-2, DZJ-5	3
	66,700	8,388	DZF-3, DZJ-6	4
	60,000	18,658	DZF-7, DZJ-10	4

[1]Failed in Weld Metal.
[2]Failed in Base Metal.
[3]Cracks in Weld Metal, Monel, and Steel.
[4]Failed in Steel.

4.2 High-Cycle Fatigue Tests. Table 4 contains the data from the high-cycle fatigue tests.

Table 4

High-Cycle Fatigue Data, Rotating Cantilever Beam Specimen, Air Environment, Smooth Specimen, 1,450 cpm

Material	Nominal Reversed Stress psi	No. of Cycles to Failure N	Specimen No.
Ni-Al Bronze Cast	40,000	282,000	DYQ-8
	35,000	1,024,000	DYQ-9
	32,000	1,727,000	DYQ-19
	30,000	61,318,000	DYQ-18
	28,500	931,000	DYQ-611
Monel "E" Cast	30,000	146,000	DZA-55
	25,000	610,00	DZA-56
	20,000	3,876,000	DZA-90
	18,500	17,730,000	DZA-191
	17,000	97,707,000	DZA-91
Valve Bronze Cast	20,000	3,000	DZU-3
	17,500	130,000	DZU-98
	15,000	250,000	DZU-8
	10,000	1,597,000	DZU-4
	8,500	9,140,000	DZU-9
Ni-Al Bronze Forged	70,000	109,000	DZE-3
	50,000	640,000	DZE-4
	50,000	1,254,000	DZE-103
	40,000	2,567,000	DZE-104
	35,000	112,344,000+	DZE-8
	30,000	106,922,000+	DZE-143

The nominal reversed stress, S_R, was calculated for this test from the applied dead-weight load and the dimensions of the specimen.

4.3 Combined Fatigue Tests. In Figures 8 through 11, the low- and high-cycle fatigue data are combined to show broad life-spectrum S_{PE} versus N curves for the two materials in this report and the two materials investigated in reference (c). The dashed curves in the figures are based on Langer's prediction equation, reference (e):

$$S_{PE} = \frac{E}{4\ N^{1/2}} \left(\ln \frac{100}{100-RA}\right) + S_E \quad ;$$

where

S_{PE} = reversed pseudoelastic stress, psi
E = modulus of elasticity, psi
N = number of cycles to failure
RA = reduction of area from a tensile test, percent
S_E = endurance limit, psi.

The solid curve is the best fit curve for the data as calculated by assuming that the actual fatigue curve would be of the same general form as Langer's equation. The equation with best fit coefficients is included in each of the figures. The corrosion-fatigue data are also shown for comparison where available.

4.4 Low-Cycle Fatigue Tests of Weldments. The results of the weldment tests are plotted in Figure 12 on the basis of S_R versus N. Included are the base metal relationship for 70-30 Cu-Ni and Monel reported previously in reference (a). The results indicate that welding had no deterimental effect on the low-cycle fatigue life when compared to the base metal.

5.0 DISCUSSION

The low-cycle fatigue curves for forged Ni-Al bronze and cast valve bronze, Figures 6 and 7, show similar behavior to previously tested nonferrous materials, in that the wrought material show little scatter of data, while the cast material exhibits the wide confidence bands characteristic of considerable scatter of data. The low-cycle fatigue behavior of the former is clearly superior to the latter.

The broad life-spectrum flexural fatigue curves, Figures 8 through 11, show that Langer's predicted curve is overly conservative for the materials considered. This behavior is typical for the cast materials previously tested and is due to the dependence of Langer's equation on the reduction of area of the material, which is low for most cast materials. The mechanical properties and fatigue curves of the forged and cast Ni-Al bronzes are very similar, as are their Langer curves. It appears that the overall effect of forging and annealing had not considerably altered the average fatigue properties of the material.

For all but one case, the corrosion-fatigue data fall near the best fit curve for the air data (Figures 8 through 11). This indicates that the saltwater environment has practically no effect on the low-cycle fatigue behavior of the materials considered.

The low-cycle fatigue behavior of all the nonferrous metals thus far included in the overall investigation are compared with respect to S_R versus N in Figure 13, and to S_{PE} versus N in Figure 14. Using the same types of curves, it was concluded in reference (b) that Monel, Superston 40, and Cufenloy 40 (drawn and stress relieved) were superior to the other materials in low-cycle flexural fatigue life in air. It is evident from Figures 13 and 14 that Ni-Al bronze, in both cast and forged conditions, ranks with these; it is also evident that the cast valve bronze shows the poorest low-cycle fatigue behavior of the materials tested.

6.0 CONCLUSIONS

The following conclusions have been reached relative to the fatigue performance of cast and forged Ni-Al bronze, cast valve bronze, and cast Monel "E":

- Both cast and forged Ni-Al bronze rank among the nonferrous materials reported as having superior low-cycle fatigue life on the basis of either nominal or pseudoelastic stress. Valve bronze has very poor low-cycle fatigue characteristics.

- Langer's predicted curve is overly conservative for the materials considered in this report.

- Saltwater corrosion does not appear to have an important effect on the low-cycle fatigue behavior of the materials reported.

It is also concluded that the low-cycle fatigue performance of 70-30 Cu-Ni welded to 70-30 Cu-Ni, Monel welded to Monel, and Monel to steel is not significantly different from that of their respective base metals.

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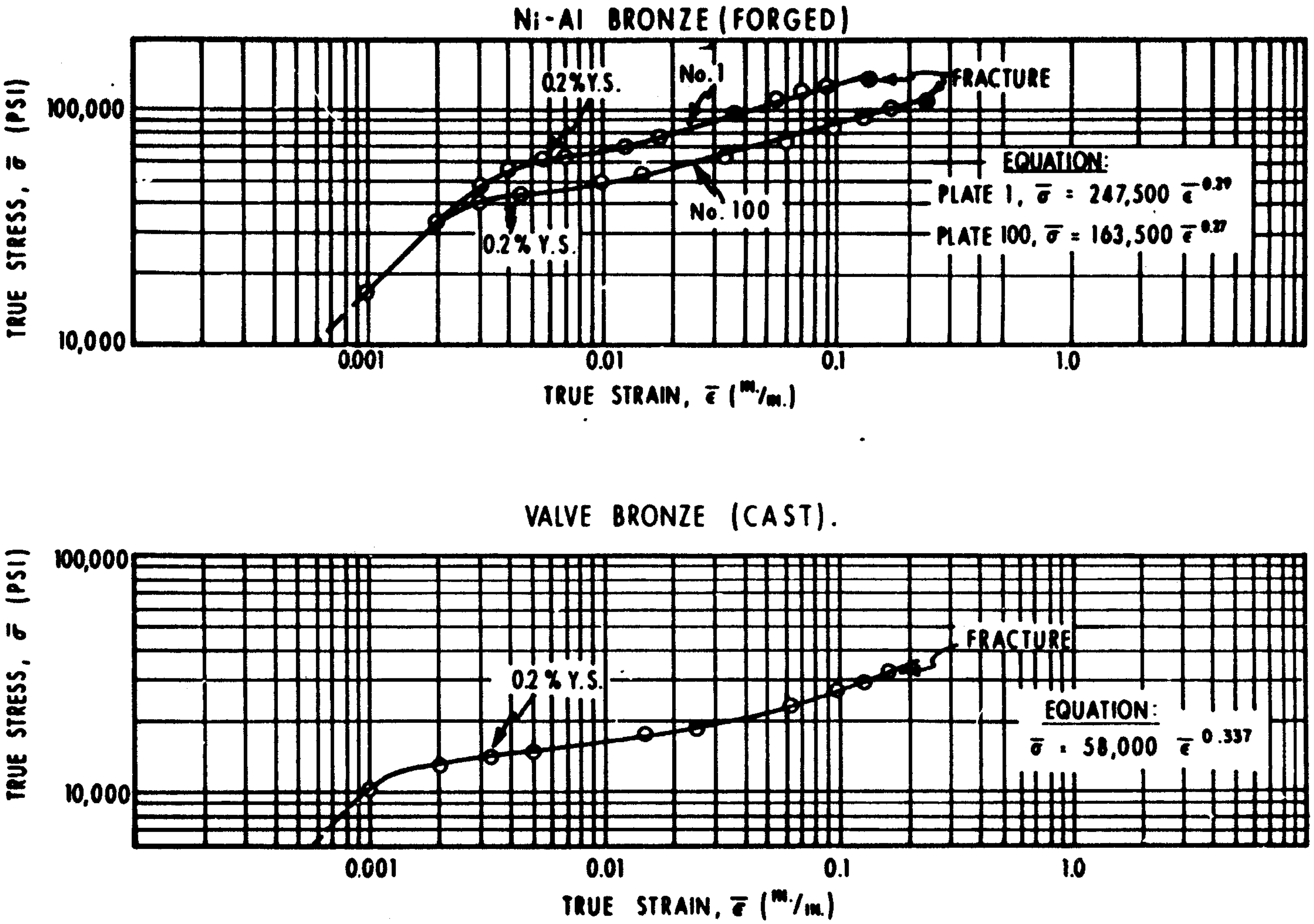

Figure 1
True-Stress Versus True Strain Relationships

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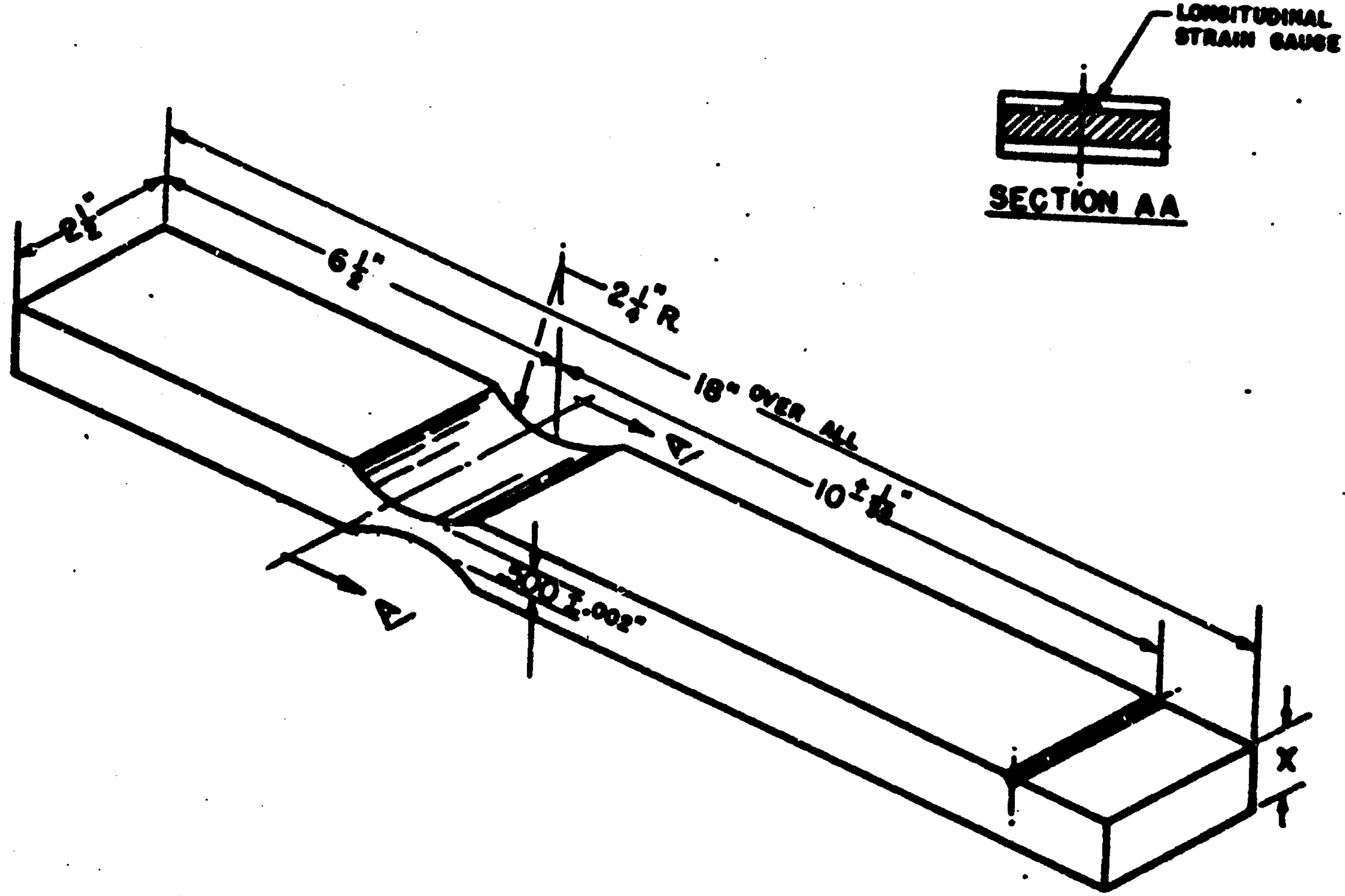

Figure 2
Low-Cycle Fatigue Specimen

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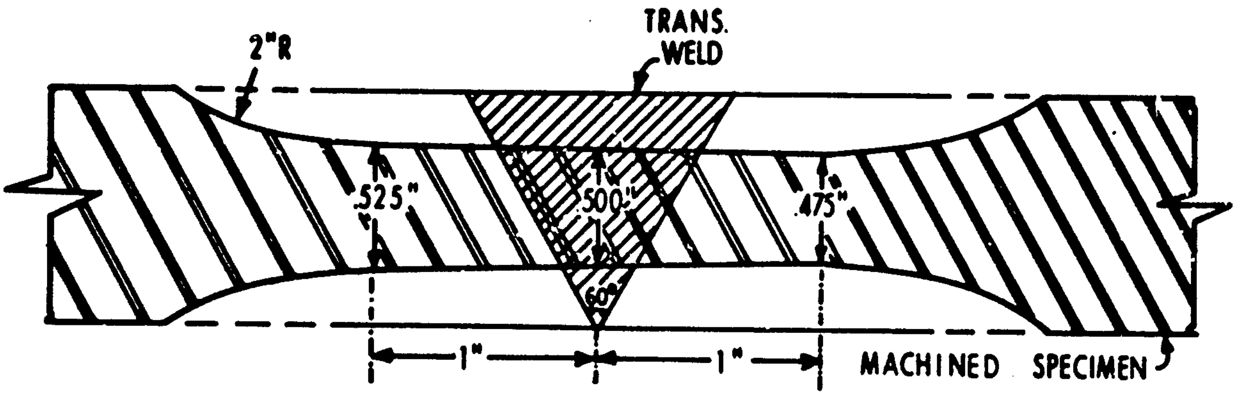

Figure 3
Longitudinal Cross-Section of Welded Constant Stress Fatigue Specimen

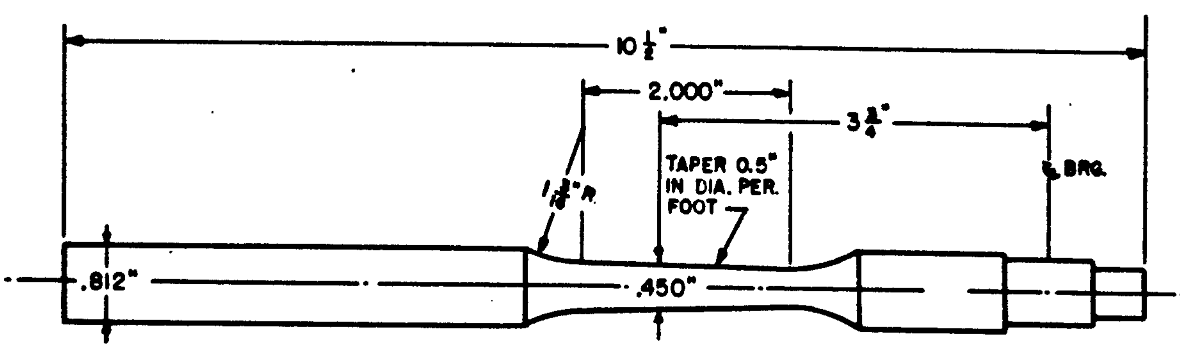

Figure 4
Rotating Cantilever Beam Fatigue Specimen

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ΔM - Moment Range
M_R - Maximum Reversed Moment
$\Delta \epsilon$ - Total Strain Range
ϵ_R - Maximum Reversed Strain
$\Delta \epsilon_p$ - Plastic Strain Range

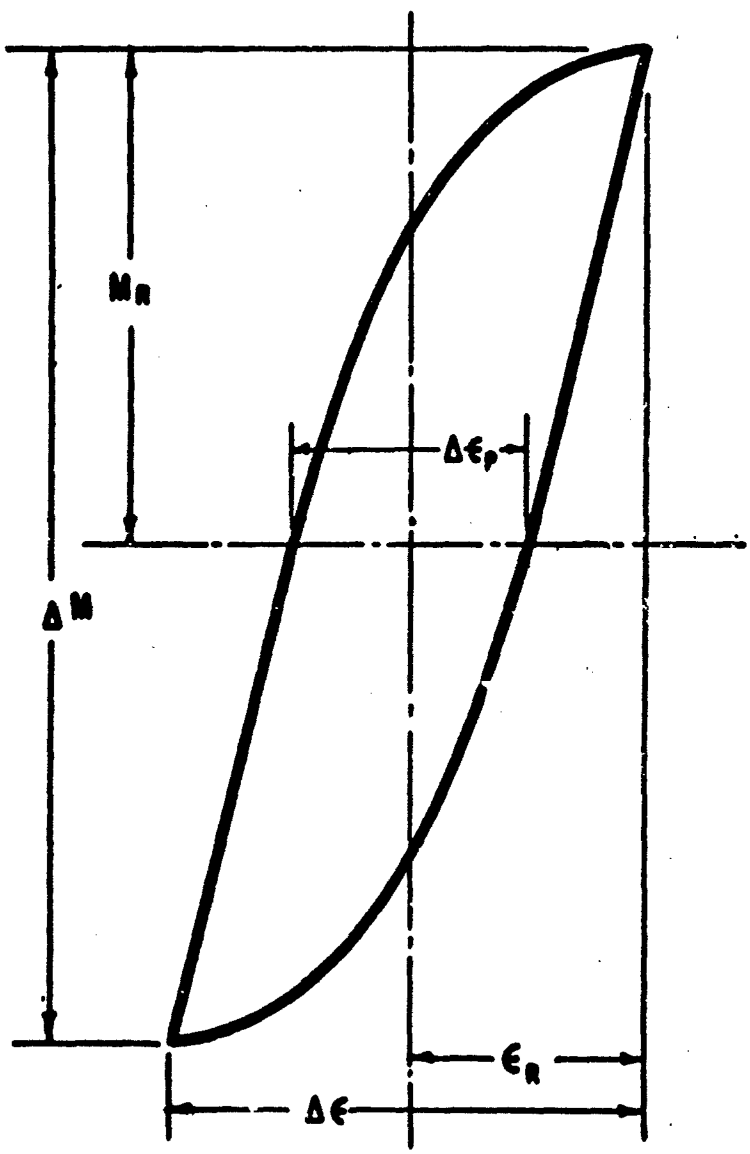

Figure 5
Typical Mechanical Hysteresis Loop and Parameters

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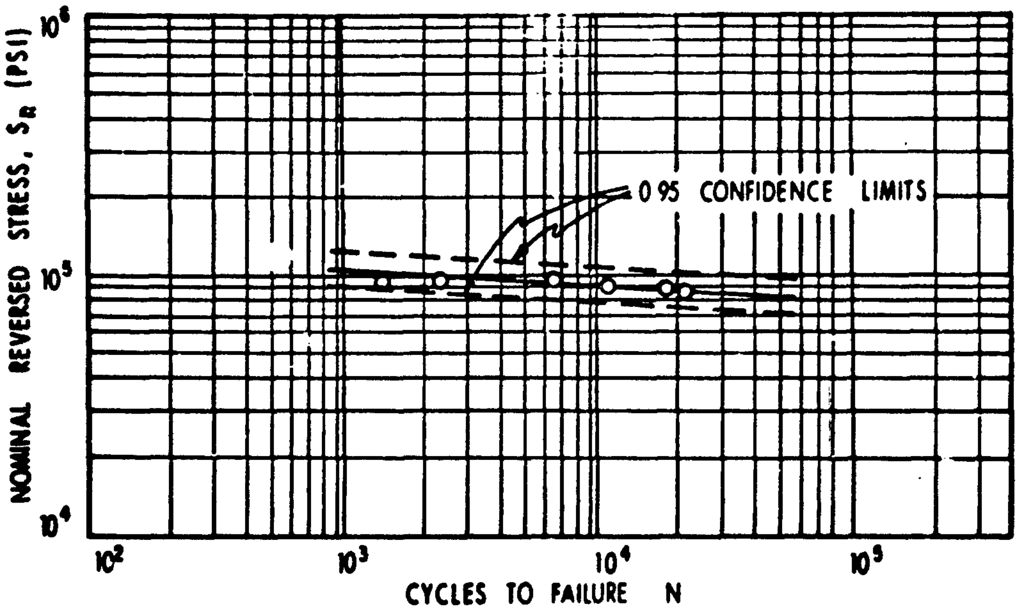
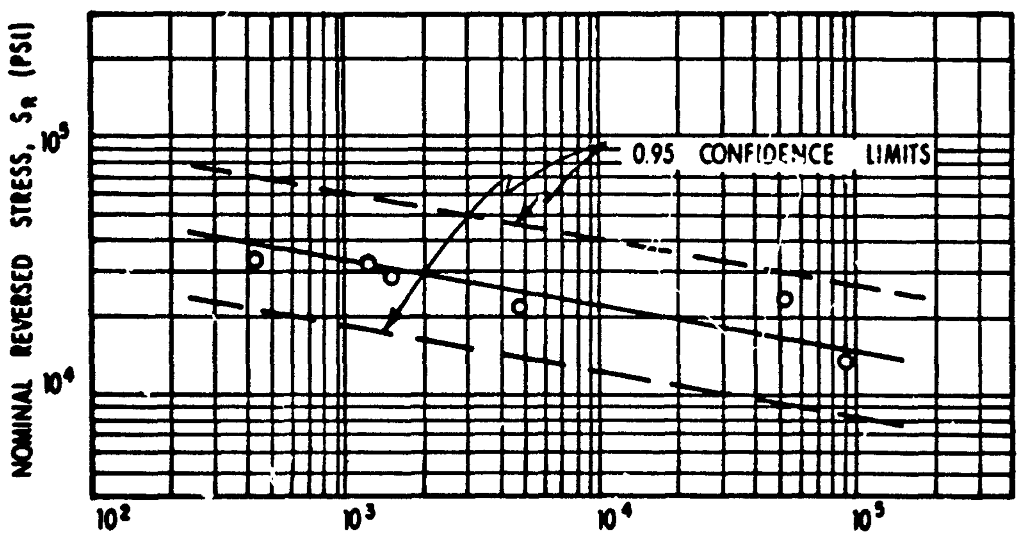


NI-AI BRONZE, FORGED, SMOOTH SURFACE, AIR ENVIRONMENT
EQUATION: $S_R N^{.06} = 156,000$



CYCLES TO FAILURE N
VALVE BRONZE, CAST; SMOOTH SURFACE; AIR ENVIRONMENT
EQUATION: $S_R N^{0.10} = 114,000$

Figure 6
Low-Cycle Flexural Fatigue, S_R Versus N

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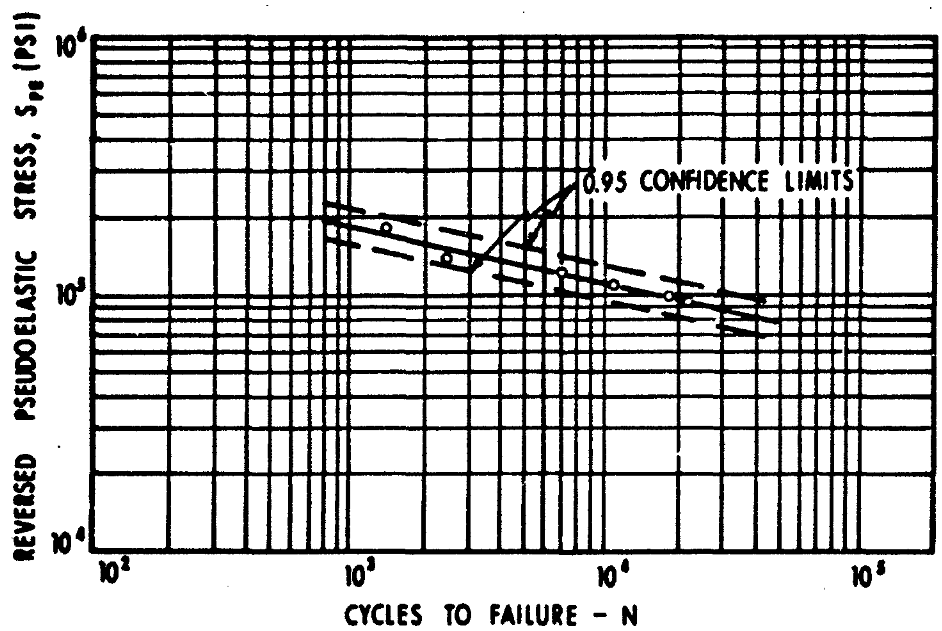
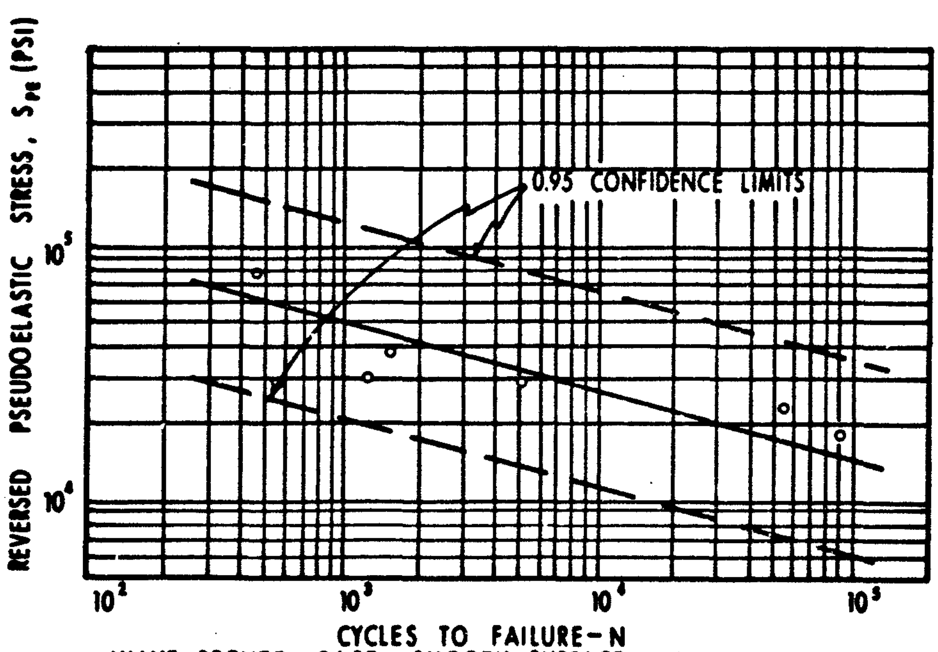


NI-AL BRONZE, FORGED; SMOOTH SURFACE; AIR ENVIRONMENT
EQUATION: $S_{PE} N^{0.22} = 862{,}000$



VALVE BRONZE, CAST; SMOOTH SURFACE; AIR ENVIRONMENT
EQUATION: $S_{PE} N^{0.27} = 327{,}000$

Figure 7
Low-Cycle Flexural Fatigue, S_{PE} Versus N

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Equation: $$S_{PE} = \frac{4.03 \times 10^5}{N^{0.32}} + 6,000$$

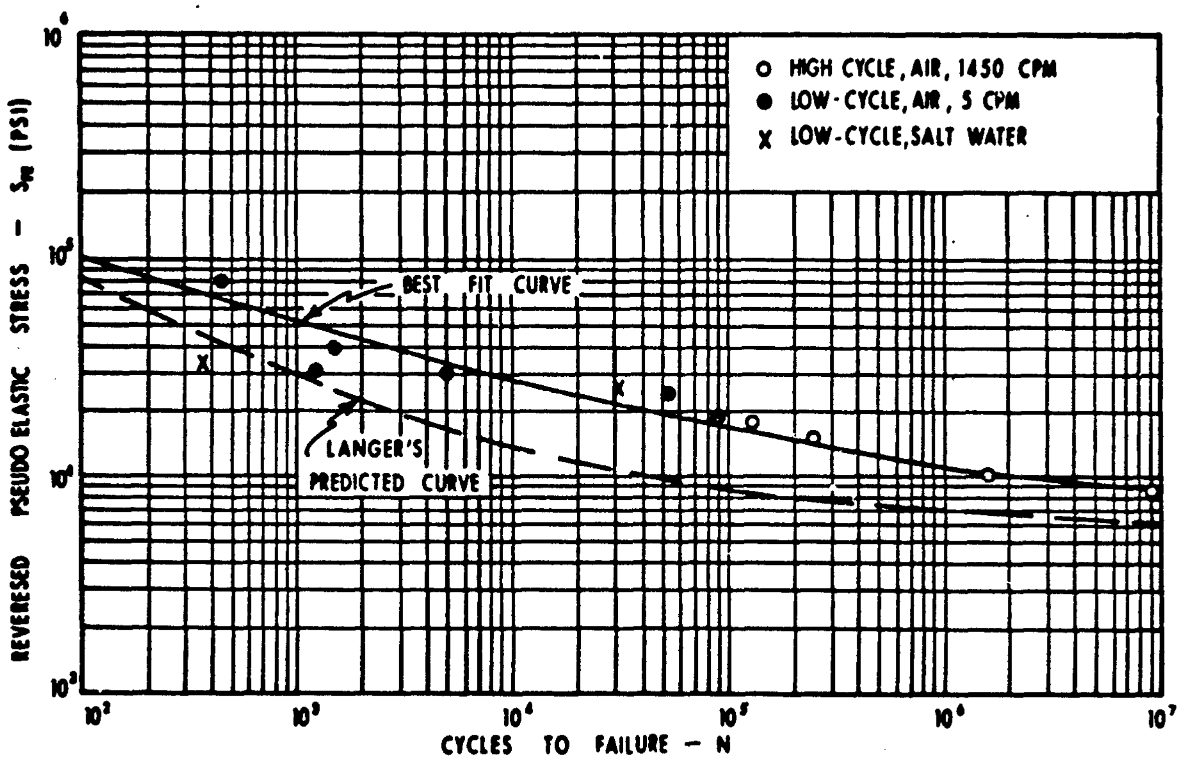

Figure 8

Flexural Fatigue Curve
Valve Bronze, Cast

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$$\text{Equation:}\quad S_{PE} = \frac{3.53 \times 10^6}{N^{0.\text{[illegible]}}} + 35{,}000$$

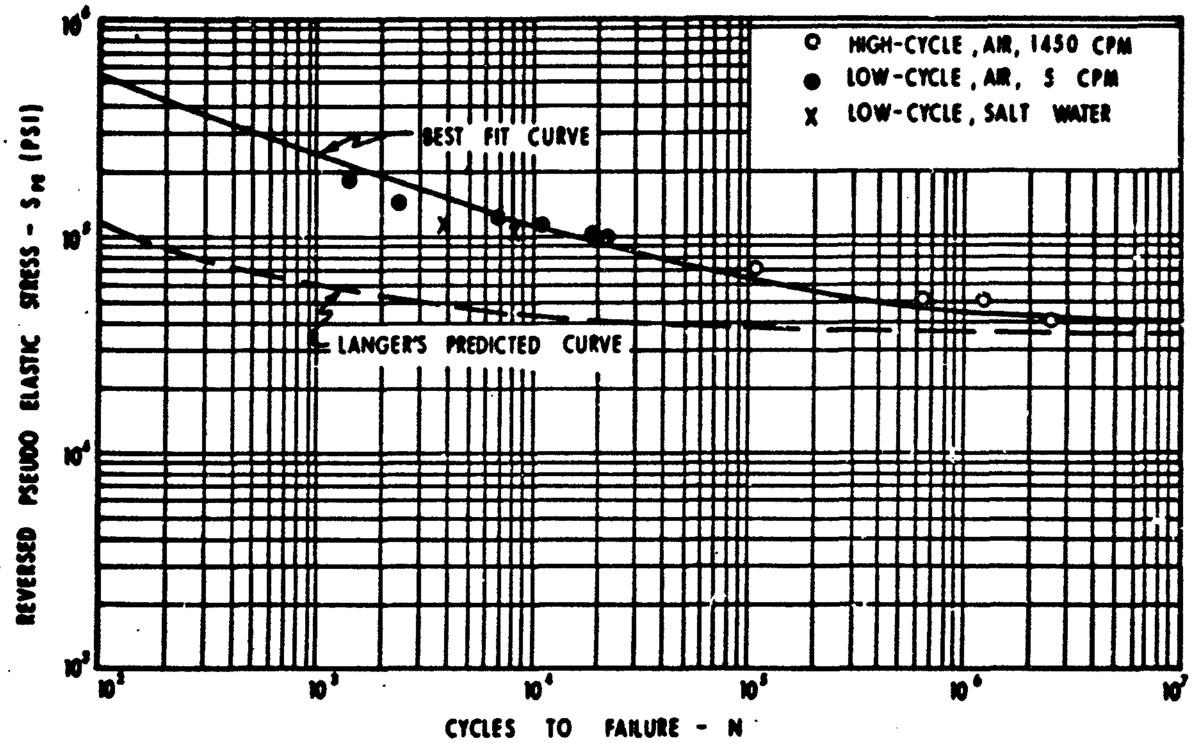

Figure 9

Flexural Fatigue Curve
Ni-Al Bronze, Forged

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Equation: $S_{PE} = \dfrac{5.57 \times 10^{6}}{N^{0.48}} + 29{,}000$

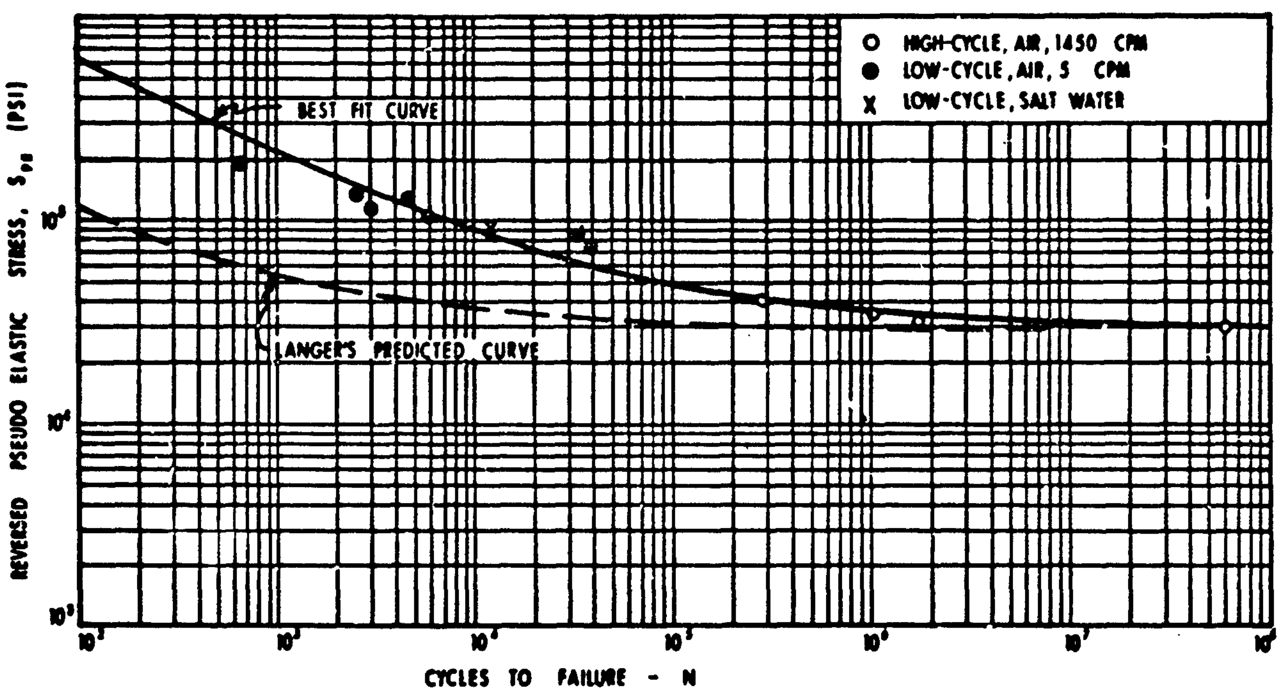

Figure 10

Flexural Fatigue Curve
Ni-Al Bronze, Cast

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Equation: $S_{PE} = \frac{2.51 \times 10^6}{N^{0.42}} + 16{,}000$

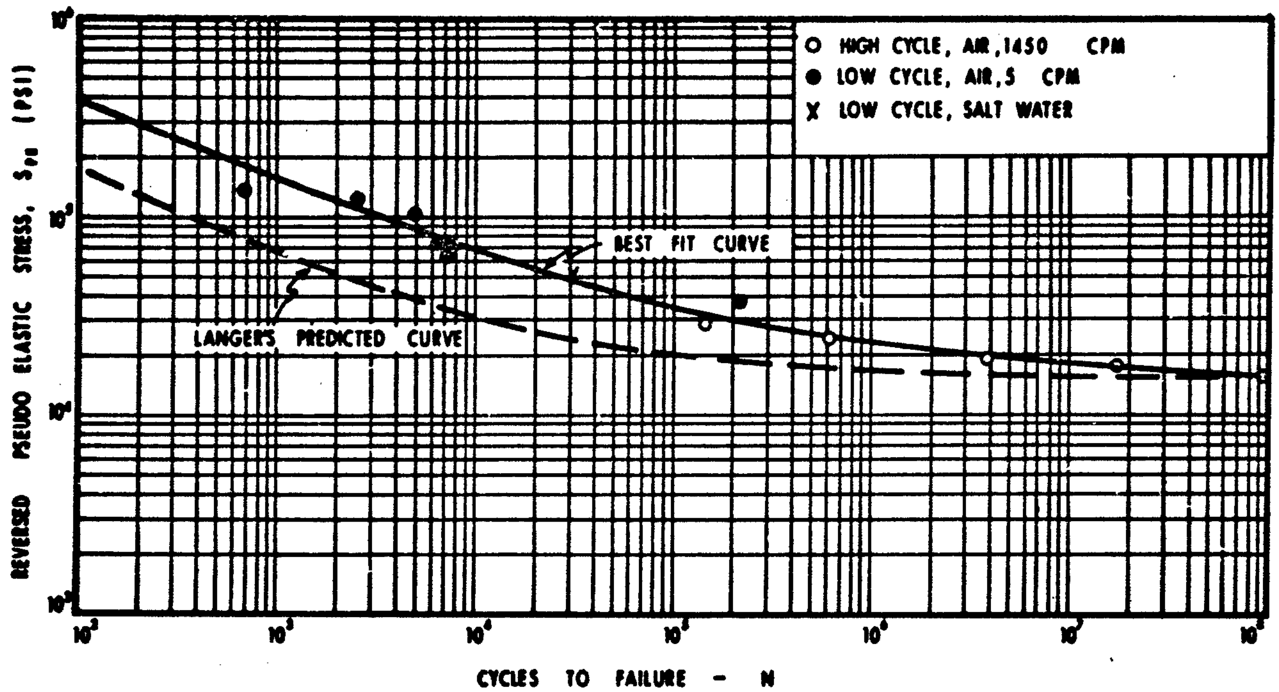

Figure 11

Flexural Fatigue Curve
Monel "E," Cast

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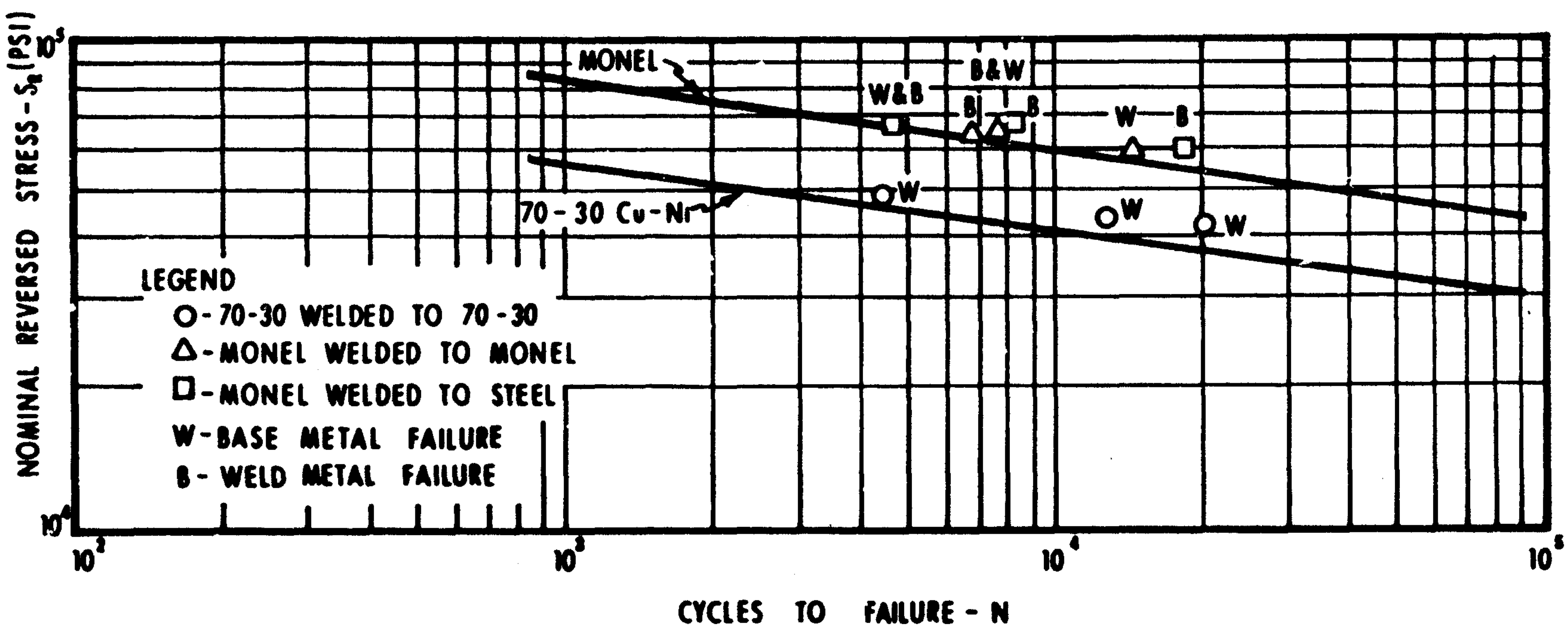

Figure 12

Flexural Fatigue Results of Welded Specimens

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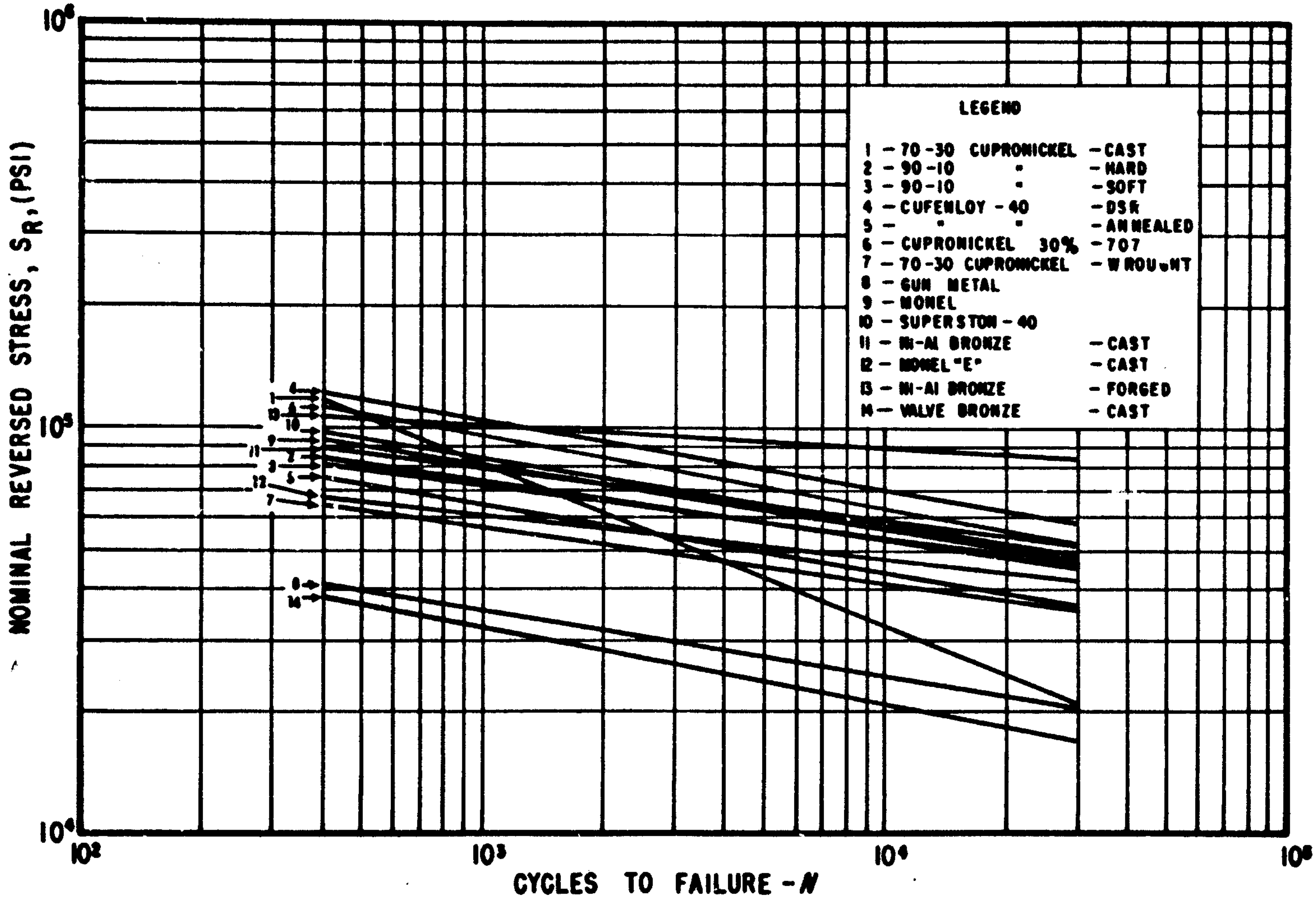

Figure 13
Low-Cycle Fatigue of Nonferrous Alloys, S_R Versus N

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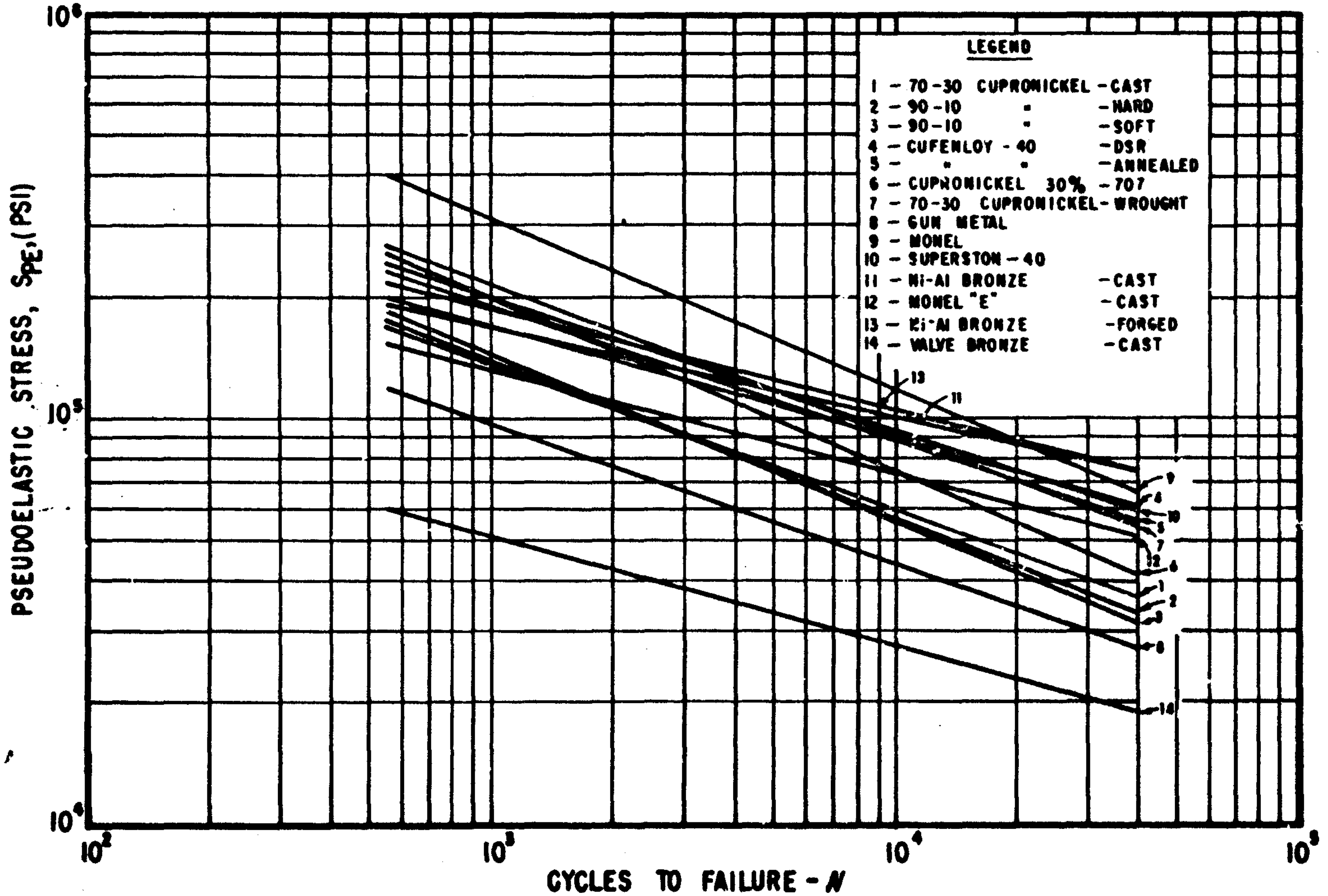

Figure 14
Low-Cycle Fatigue of Nonferrous Metals, S_{PE} Versus N

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13. ABSTRACT

This is the fourth phase report of an investigation of the low-cycle fatigue behavior of nonferrous alloys for submarine heat exchanger and saltwater piping applications. The low-cycle fatigue behavior of forged Ni-Al bronze and cast valve bronze was investigated in both air and salt water. The flexural fatigue behavior of these two materials, together with cast Ni-Al bronze and cast Monel "E" of phase three, were compared to that predicted by Langer's equation. It was concluded that Langer's equation was overly conservative for the materials reported, and that saltwater corrosion has very little effect on low-cycle fatigue life. Both cast and forged Ni-Al bronze rank as superior, whereas valve bronze ranks poorly as far as low-cycle fatigue performance is concerned.

(Authors)

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Low-cycle fatigue Flexural fatigue Nonferrous alloys Valve bronze Ni-Al bronze Langer's equation						

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